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4. TITLE AND SUBTITLE Collaborative Autonomous Unmanned Aerial – Ground Vehicle Systems for Field Operations (Proposal Number: 50153-CI) Final Report			5a. CONTRACT NUMBER W911NF-06-1-0069		
			5b. GRANT NUMBER		
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6. AUTHORS KIMON P. VALAVANIS			5d. PROJECT NUMBER		
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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of South Florida - Tampa 4202 East Fowler Ave.  Tampa, FL 33620 -			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
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13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT A heterogeneous UAV-UGV system with adaptable operational procedures/protocols for asset coordination, cooperation, decision-making, efficient communication and processing between its assets, meeting mission objectives is modeled and evaluated experimentally, by simulation and using prototype systems. The research has resulted in i) Development of a processing system for UGVs/UAVs that incorporate an on-board processing vision systems using low cost and highly adaptable motherboards meeting strict payload capabilities of miniature aerial vehicles and ground vehicles, including building and testing of four UGVs and one unmanned helicopter that utilize this system; ii) Development of a proposed FPGA based					
15. SUBJECT TERMS Autonomous, Unmanned, Aerial Vehicles, Ground Vehicles, Swarms, Navigation					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Kimon Valavanis
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER 545-674-6564

## Report Title

Collaborative Autonomous Unmanned Aerial – Ground Vehicle Systems for Field Operations  
(Proposal Number: 50153-CI)  
Final Report

### ABSTRACT

A heterogeneous UAV-UGV system with adaptable operational procedures/protocols for asset coordination, cooperation, decision-making, efficient communication and processing between its assets, meeting mission objectives is modeled and evaluated experimentally, by simulation and using prototype systems. The research has resulted in i) Development of a processing system for UGVs/UAVs that incorporate an on-board processing vision systems using low cost and highly adaptable motherboards meeting strict payload capabilities of miniature aerial vehicles and ground vehicles, including building and testing of four UGVs and one unmanned helicopter that utilize this system; ii) Development of a proposed FPGA based autopilot design that allows for future system improvements by providing an easily programmed, dedicated hardware platform that will work with extremely small payload capacity vehicles and compliment the existing system by removing tight timing requirements for low level controls and data acquisition from the existing processing system; iii) Designing and testing decentralized PID and fuzzy logic, LQR, and model predictive controllers for small unmanned helicopters; iv) Testing and implementing in hardware UGVs as heterogeneous swarms not maintaining one particular formation but having the ability to modify formation in the event of member or configuration loss, or addition of new team member; v) Incorporating MANET technology to allow a group of vehicles to extend the area of coverage by relying information from distant sources to the main station through 'routing' vehicles; vi) Development of localization techniques and vision based navigation; vii) Development of a proposed design for a UGV based mobile landing platform along with an analysis of available batteries and power requirements that led to recommendations for improvement of the endurance; viii) Development of an automated process for controller design, validation and hardware implementation utilizing off-the-shelf MATLAB/Simulink tools; ix) Development of algorithms for vision based traffic monitoring utilizing helicopters with the developed on-board vision system.

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### List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

#### (a) Papers published in peer-reviewed journals (N/A for none)

- D. Ernst, K. Valavanis, J. Craighead, "Unmanned Vehicle Controller Design, Evaluation and Implementation: From MATLAB to Printed Circuit Board", Journal of Intelligent and Robotic Systems, May 2007.
- L. Barnes, W. Alvis, M. Fields, K. Valavanis, W. Moreno, "Heterogeneous Swarm Formation Control with Potential Fields Formed by Bivariate Normal Functions" International Journal on Systems Science and Applications, Vol. 2, No. 4, pp: 346-359, February 2007.
- A. Tsalatsanis, K. Valavanis, N. Tsourveloudis, "Mobile Robot Navigation Using Sonar and Range Measurements from Uncalibrated Cameras", Journal of Intelligent and Robotic Systems, Vol. 48, No. 2, pp: 253-284, February 2007.
- A. Tsalatsanis, K. Valavanis, A. Yalcin, Vision Based Target Tracking and Collision Avoidance for Mobile Robots, Journal of Intelligent and Robotic Systems, Vol. 48, No. 2, pp: 285-304, February 2007.
- R. Garcia, K. P. Valavanis, "Improving and Miniaturizing an On-board Processing System for Small Unmanned Vehicles", Unmanned Systems, Vol. 24, No. 5, pp: 36-39, September / October 2006 (Invited).
- C. L. Castillo, W. Alvis, M. Castillo-Effen, W. Moreno, K. Valavanis, "Small Unmanned Helicopter Simplified and Decentralized Optimization-based Controller Design for Non-aggressive Flights", International Journal on Systems Science and Applications, Vol. 1, No. 3 (2006), pp: 303-315.
- Spanoudakis, P.S., Tsourveloudis, N.C., Valavanis, K.P., "Design Considerations of a Prototype VTOL Robotic Vehicle through Market Survey Data Collection", Journal of Intelligent and Robotic Systems, Vol. 46, No. 4, pp 339-364, August 2006.

Number of Papers published in peer-reviewed journals: 7.00

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#### (b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

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#### (c) Presentations

All conference papers have been presented at the corresponding meetings.

**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

NONE!

All peer-reviewed papers.

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

0

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

- Monteriu, A., Asthana, P., Valavanis, K., Longhi, S., "Residual Generation Approaches in Navigation Sensors Fault Detection Applications", CD-ROM Proceedings, European Control Conference, Kos, Greece, July 2007.
- Alzate, Marco A., Slamanca, Maria P., Pena, Nester M., Labrador, Miguel A., "End-to-End Mean Bandwidth Estimation as a Function of Packet Length in Mobile Ad Hoc Networks", Proceedings of ISCC 2007, June 2007.
- Tsalatsanis, A., Valavanis, K. P., Kandel, A., Yalcin, A., "Multiple Sensor Based UGV Localization Using Fuzzy Extended Kalman Filtering", CD-ROM Proceedings, 15th Mediterranean Conference on Control and Automation, MED'07, June 27-29, 2007, Athens, Greece.
- Castillo, C. L., Moreno, W., Valavanis, K. P., "Unmanned Helicopter Waypoint Trajectory Tracking Using Model Predictive Control", CD-ROM Proceedings, 15th Mediterranean Conference on Control and Automation, MED'07, June 27-29, 2007, Athens, Greece.
- Ramarathinam, V., Labrador, M., "Communication-assisted Topology Control for Autonomous Unmanned Systems", CD-ROM Proceedings, 15th Mediterranean Conference on Control and Automation, MED'07, June 27-29, 2007, Athens, Greece.
- Barnes, L., Fields, M. A., Valavanis, K., "Unmanned Ground Vehicle Swarm Formation Control Using Potential Fields", CD-ROM Proceedings, 15th Mediterranean Conference on Control and Automation, MED'07, June 27-29, 2007, Athens, Greece.
- Alvis, W., Murthy, S., Valavanis, K., Moreno, W., Katkooi, S., "FPGA Based Flexible Autopilot Platform for Unmanned Systems", CD-ROM Proceedings, 15th Mediterranean Conference on Control and Automation, MED'07, June 27-29, 2007, Athens, Greece.
- Puri, A., Valavanis, K. P., Kontitsis, M., "Statistical Profile Generation for Traffic Monitoring Using Real-time UAV-based Traffic Video Data", CD-ROM Proceedings, 15th Mediterranean Conference on Control and Automation, MED'07, June 27-29, 2007, Athens, Greece.
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- Castillo-Effen, M., Moreno, W.A., Labrador, M.A., Valavanis, K.P., "Adapting Sequential Monte-Carlo Estimation to Cooperative Localization in Wireless Sensor Networks", Proceedings of the 3rd IEEE International Conference on Mobile Ad-Hoc and Sensor System (MASS 2006), Workshop on Localized Communication and Topology Protocols for Ad Hoc Networks (LOCAN 2006), October 2006.
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- Valavanis, K., "Unmanned Vehicle Navigation and Control: A Fuzzy Logic Perspective", Proceedings of the IEEE Conference on Evolutionary Fuzzy Systems, UK, September, 2006.
- Barnes, L., Alvis, W., Fields, M. A., Valavanis, K., Moreno, W., "Heterogeneous Swarm Formation Control Using Bivariate Normal Functions to Generate Potential Fields", Proceedings of the IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and Its Applications (DIS'06), Prague, June 2006.
- Barnes, L.E., Alvis, W., Fields, M., Valavanis, K., Moreno, W., "Swarm Formation Control with Potential Fields Formed by Bivariate Normal Functions", CD-ROM Proceedings, 14th Mediterranean Conference on Control and Automation, Ancona, Italy, June 2006.
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- Lin, P-S., Puri, A., Hagan, L., Valavanis, K., "Automatic Transformation of Video Image Data from UAVs into Traffic Information for Simulation Model Calibration", Proceedings 13th World Congress, London, October 2006.
- Ernst, D., Valavanis, K., Craighead, J., "Automated Process for Unmanned Systems Controller Implementation Using MATLAB", CD-ROM Proceedings, 14th Mediterranean Conference on Control and Automation, Ancona, Italy, June 2006.
- Monteriu, A., Asthana, P., Valavanis, K., Longhi, S., "Experimental Validation of a Real-Time Sensor-Based Fault Detection and Isolation System for Unmanned Ground Vehicles", CD-ROM Proceedings, 14th Mediterranean Conference on Control and Automation, Ancona, Italy, June 2006.
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- Garcia, R., Valavanis, K., Kontitsis, M., "A Multiplatform On-board Processing System for Miniature Unmanned Vehicles", CD-ROM Proceedings, IEEE International Conference on Robotics and Automation, Orlando, Florida, May 2006.

(d) Manuscripts

1. Manuscript under preparation to be published by Springer, on Sensor-based control of small unmanned rotorcraft.
2. Monograph to be published by Springer on Integration of UAS into the NAS.

Both books will acknowledge the support of the ARO through this funded project.

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT SUPPORTED
Richard Garcia	0.20
Laura Barnes	0.20
Wendy Alvis	0.20
M. Castillo-Effen	0.40
C. Castillo	0.40
D. Ernst	0.50
M. Kontitsis	0.20
A. Tsalatsanis	0.25
FTE Equivalent:	2.35
Total Number:	8

Names of Post Doctorates

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT SUPPORTED	National Academy Member
K. P. Valavanis	0.25	No
M. Labrador	0.15	No
W. Moreno	0.15	No
FTE Equivalent:	0.55	
Total Number:	3	

Names of Under Graduate students supported

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 0.00

### Names of Personnel receiving masters degrees

#### NAME

Richard Garcia

Daniel Ernst

**Total Number:**

2

### Names of personnel receiving PhDs

#### NAME

Richard Garcia

Laura Barnes

Wendy Alvis

M. Castillo-Effen

**Total Number:**

4

### Names of other research staff

#### NAME

#### PERCENT SUPPORTED

**FTE Equivalent:**

**Total Number:**

### Sub Contractors (DD882)

**Inventions (DD882)**

# **Collaborative Autonomous Unmanned Aerial – Ground Vehicle Systems for Field Operations**

**(Proposal Number: 50153-CI)**

BAA Solicitation Number W911NF-04-R-0005  
Research Area “Computing and Information Science”  
Program 5.3: The Systems and Control Program

Technical Point of Contact: Dr. Randy Zachery  
[Randy.Zachery@us.army.mil](mailto:Randy.Zachery@us.army.mil)  
Tel: (919) 549-4368

**Award Number: W911NF061069**

**Final Report Submitted by**

**Kimon P. Valavanis**  
**August 31, 2007**

## **1 Agency Use Only**

## **2 REPORT DATE**

August 31, 2007

## **3 REPORT TYPE AND DATES COVERED**

Final Report: March 2006, to August 31 2007

## **4 TITLE AND SUBTITLE**

Collaborative Autonomous Unmanned Aerial – Ground Vehicle Systems for Field Operations

Proposal Number: 50153-CI

PI/PD: Kimon P. Valavanis, University of South Florida

## **5 FUNDING NUMBERS**

Award Number: W911NF061069

## **6 AUTHORS**

Report Authors: Drs. Kimon P. Valavanis Wilfrido Moreno, Miguel Labrador

Graduate Student Coordinator: Ms. Wendy Alvis, PhD Candidate

## **7 PERFORMING ORGANIZATION NAME AND ADDRESS**

University of South Florida - Tampa

4202 East Fowler Ave.

Tampa, FL 33620

## **8 PERFORMING ORGANIZATION REPORT NUMBER**

N/A



## **9 SPONSORING/MONITORING AGENCY NAME AND ADDRESS**

U.S. Army Research Office  
P.O. Box 12211  
Research Triangle Park, NC 27709-2211

## **10 SPONSORING/MONITORING AGENCY REPORT NUMBER**

**Proposal Number: 50153-CI, Award Number: W911NF061069**

## **11 SUPPLEMENTARY NOTES**

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## **12a DISTRIBUTION AVAILABILITY STATEMENT**

Approved for Public Release; Distribution Unlimited

## **13. ABSTRACT**

A heterogeneous UAV-UGV system with adaptable operational procedures/protocols for asset coordination, cooperation, decision-making, efficient communication and processing between its assets, meeting mission objectives is modeled and evaluated experimentally, by simulation and using prototype systems. The research has resulted in i) Development of a processing system for UGVs/UAVs that incorporate an on-board processing vision systems using low cost and highly adaptable motherboards meeting strict payload capabilities of miniature aerial vehicles and ground vehicles, including building and testing of four UGVs and one unmanned helicopter that utilize this system; ii) Development of a proposed FPGA based autopilot design that allows for future system improvements by providing an easily programmed, dedicated hardware platform that will work with extremely small payload capacity vehicles and compliment the existing system by removing tight timing requirements for low level controls and data acquisition from the existing processing system; iii) Designing and testing decentralized PID and fuzzy logic, LQR, and model predictive controllers for small unmanned helicopters; iv) Testing and implementing in hardware UGVs as heterogeneous swarms not maintaining one particular formation but having the ability to modify formation in the event of member or configuration loss, or addition of new team member; v) Incorporating MANET technology to allow a group of vehicles to extend the area of coverage by relying information from distant sources to the main station through 'routing' vehicles; vi) Development of localization techniques and vision based navigation; vii) Development of a proposed design for a UGV based mobile landing platform along with an analysis of

available batteries and power requirements that led to recommendations for improvement of the endurance; viii) Development of an automated process for controller design, validation and hardware implementation utilizing off-the-shelf MATLAB/Simulink tools; ix) Development of algorithms for vision based traffic monitoring utilizing helicopters with the developed on-board vision system.

## REPORT DOCUMENTATION PAGE (SF298)

### (CONTINUATION SHEET)

#### ***Number of Peer Reviewed Papers – See list below***

##### List of Published Peer Reviewed Conference Papers

- Monteriu, A., Asthana, P., Valavanis, K., Longhi, S., “*Residual Generation Approaches in Navigation Sensors Fault Detection Applications*”, CD-ROM Proceedings, European Control Conference, Kos, Greece, July 2007.
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- Castillo-Effen, M., Moreno, W.A., Labrador, M.A., Valavanis, K.P., “*Adapting Sequential Monte-Carlo Estimation to Cooperative Localization in Wireless Sensor Networks*”, Proceedings of the 3rd IEEE International Conference on Mobile Ad-Hoc and Sensor System (MASS 2006), Workshop on Localized Communication and Topology Protocols for Ad Hoc Networks (LOCAN 2006), October 2006.
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- Dalamagkidis, K., Ioannou, S., Valavanis, K. P., Stefanakos, E., “*A Mobile Landing Platform for Miniature Vertical Take-Off and Landing Vehicles*”, CD-ROM Proceedings, 14<sup>th</sup> Mediterranean Conference on Control and Automation, Ancona, Italy, June 2006.
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#### List of Published Peer Reviewed Journal Papers

- D. Ernst, K. Valavanis, J. Craighead, “*Unmanned Vehicle Controller Design, Evaluation and Implementation: From MATLAB to Printed Circuit Board*”, Journal of Intelligent and Robotic Systems, May 2007.
- L. Barnes, W. Alvis, M. Fields, K. Valavanis, W. Moreno, “*Heterogeneous Swarm Formation Control with Potential Fields Formed by Bivariate Normal Functions*” International Journal on Systems Science and Applications, Vol. 2, No. 4, pp: 346-359, February 2007.
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- A. Tsalatsanis, K. Valavanis, A. Yalcin, “*Vision Based Target Tracking and Collision Avoidance for Mobile Robots*”, Journal of Intelligent and Robotic Systems, Vol. 48, No. 2, pp: 285-304, February 2007.
- R. Garcia, K. P. Valavanis, “*Improving and Miniaturizing an On-board Processing System for Small Unmanned Vehicles*”, Unmanned Systems, Vol. 24, No. 5, pp: 36-39, September / October 2006 (**Invited**).
- C. L. Castillo, W. Alvis, M. Castillo-Effen, W. Moreno, K. Valavanis, “*Small Unmanned Helicopter Simplified and Decentralized Optimization-based Controller Design for Non-aggressive Flights*”, International Journal on Systems Science and Applications, Vol. 1, No. 3 (2006), pp: 303-315.
- Spanoudakis, P.S., Tsourveloudis, N.C., Valavanis, K.P., “*Design Considerations of a Prototype VTOL Robotic Vehicle through Market Survey Data Collection*”, Journal of Intelligent and Robotic Systems, Vol. 46, No. 4, pp 339-364, August 2006.

#### List of Accepted / Submitted Peer Reviewed Papers

- Castillo-Effen, M., Castillo, C.L., Moreno, W.A., Valavanis, K.P., “*Robustification of Decentralized PID Control for Small Unmanned Rotorcraft*”, CD-ROM Proceedings, IEEE/RSJ International Conference on Intelligent Robots and Systems, Oct 29-Nov 2, 2007, San Diego, California, ACCEPTED.

- Ioannou, S., Dalamagkidis, K., Valavanis, K. P., Stefanakos, E.K., Wiley, P.H., “*On Improving Endurance of Unmanned Ground Vehicles: The ATRV-Jr Case Study*”, Under review, Journal of Intelligent and Robotic Systems..
- Castillo-Effen, M., Labrador, Moreno, W.A, Valavanis, K.P., “*Probabilistic Estimation Algorithm for Cooperative Localization in Wireless Sensor Networks*”, Submitted for review in International Journal of Parallel, Emergent and Distributed Systems.

## ***Number of Manuscripts***

## ***Number of Books: 1***

### Published Book

K. P. Valavanis, Editor, Advances In Unmanned Aerial Vehicles: State of the Art and the Road to Autonomy, ISBN: 978-1-4020-6113-4, Springer, June 2007.

## ***Honors and Awards***

Richard D. Garcia, Advisor Kimon P. Valavanis: Best PhD Thesis Project, USF Computer Science and Engineering Award.

## **Scientific Progress and Accomplishments**

Research progress is reported in separate section documents according to proposal objectives. Details, results and block diagrams may be found in the published papers and the book.

### Miniaturized On-Board Processing System for VTOLs and UGVs

A high powered miniaturized and very light-weighted on-board processing system has been designed for Unmanned Vehicles (UVs). It employs safe control of UVs and high power on-board processing while offsetting cost with advanced Commercial off the Shelf (COTS) hardware. It has been implemented and tested experimentally on small unmanned Vertical Takeoff and Landing (VTOL) helicopters, as well as on small unmanned ground Radio Controlled (RC) mobile vehicles, custom made and modified for quick and easy deployment (maximum efficiency). This entails efficiency of the platform itself, efficiency of on-board components, and efficiency of the system as a whole – including, but not limited to, sensor and processing system switching between vehicles in minimum time. For the on-board processing system under consideration, the turn around time to ‘un-plug’ it from one vehicle and ‘plug-it-in’ another, is less than 15 minutes!

The central objective is to design and implement an on-board processing system that meets very limited payload capabilities of small UVs, sacrificing minimal computational power and run time, adhering at the same time to the low cost nature of commercial Radio Controlled (RC) equipment. Although on-board processing systems for full scale unmanned (aerial) vehicles is a well researched area, there is still work to be done for small scale UVs.

A major constraint and, at the same time, design requirement of the proposed system is cost effectiveness, at least one order of magnitude less, when compared to other systems with similar capabilities, like the USC AVATAR (Autonomous Vehicle Aerial Tracking and Reconnaissance) system. The overall cost of the proposed on-board processing system as well as the cost of a small / miniature platform like the RAPTOR 90 SE, Joker Electric, TREX Micro Electric helicopters, or custom made E-MAXX RC Truck ground mobile platforms fully loaded with sensors, does not exceed \$15K! Thus, the unmanned vehicles' overall potential is increased due to its "use-n-lose" ability, which allows for dull, dirty and dangerous deployment missions without the need for recovery.

Unmanned vehicles specifically designed for quick and easy deployment require maximum efficiency. This entails efficiency of the platform itself, efficiency of on-board components, and efficiency of the system as a whole – including, but not limited to, sensor and processing system switching between vehicles in minimum time. As a result, this allows individual resources to share components, stretching overall resources without jeopardizing response time or effectiveness. This 'enhanced ability' has served as one reference point for the designed on-board processing system; the turn around time to 'un-plug' it from one vehicle and 'plug-it-in' another, is less than 15 minutes!

Performed experiments with small helicopters have revealed realistic payload limitations are around 8.5 pound for a typical small UV platform like the RAPTOR 70 & 90 SE, creating major restrictions on devices placed on-board the platform. This limitation is the main justification for alternative solutions like off-board processing, where UVs are typically equipped with only lightweight cameras and transmitters. Transmitted data is then used by ground processing systems to perform all necessary computations. This transmitted data, however, introduces both noise and data loss to the processing system due to limitations of wireless communication. Transmitted video is commonly littered with static and color rearrangements and it is typical to observe complete video dropout due to lost communication or bandwidth limitations. Wireless transmission also entails serious security issues with transmitted data being maliciously damaged or stolen. Software encryption only adds to computational demands, and hardware encryption taxes the already limited payload of the platform. Hence, the preference to on-board processing is well justified.

The hardware components of the on-board processing system consist of:

- 2.0 GHz Pentium Processor mounted on a mini - ITX motherboard;
- Sony Block Camera (two used on UGV for stereo vision);
- Microstrain 3DM-G IMU;
- 2 Gigs 333 MHz RAM;
- 4 channel Frame Graber;
- Superstar-2 GPS receiver;
- Servo controller / Safety switch;

- 120 W Power Supply;
- 11.1 V LiPo Battery;
- 802.11B/G Mini-PCI wireless card.

This particular hardware configuration has been chosen because of its high computational capabilities, low power consumption, multiple I/O ports, size, low heat emission and cost. This on-board system is packaged into a 23 cm x 18 cm x 6 cm plywood box. Its total weight is less than 3 pounds! This 'box' is easily mounted in multiple configurations depending on the desired platform. For small helicopters, the slim design of the enclosure allows for mountings that minimally affect the center of gravity (CG) of the unmanned aerial vehicle. The box is coated with EM foil. Plywood has been chosen for the enclosure due to its lightweight nature and its lack of electrical conductance.

The on-board the helicopter camera is mounted on a pan/tilt mechanism. Several variations of the pan/tilt have been designed and tested, all of which are controlled by two pulse width modulation (PWM) servos, allowing for control of widely varying pan/tilts without hardware modifications. Servo commands are issued by the Servo/Safety switch located within the enclosure. The main purpose of the Servo/Safety switch is to account for manual takeover in the event the vehicle becomes unstable under computer control.

A custom designed breakout board allows interfacing with the Servo/Safety switch. This has been preferred over a breakout cable to limit unused wires in the on-board system. The interface allows for nine PWM inputs, one of which must be the manual/computer designator switch, and nine PWM outputs from the Servo/Safety switch. The breakout board also allows the Servo/Safety switch to be powered by the mini-ITX power supply, or a separate power source, adding for some level of safety in case the mini-ITX power supply or power source fail during flight. The breakout board has both a regulated 5V and unregulated 12V output to allow powering of external sensors. To satisfy the need for orientation data required by many software algorithms, a Microstrain 3-DMG has been mounted on the platform. This device gives the on-board system access to the current orientation of the platform at up to 100 Hz. The sensor is capable of sending both raw and gyro stabilized data and can return Euler angles, Quaternion vectors, roll rates, accelerations, and magnetic direction.

Power for the on-board system is supplied via the 11.1V 4.2 Ah Lithium Polymer (LiPo) battery. LiPo batteries have been selected due to their high power to weight ratio, small packaging, and wide operating temperatures. Power distribution is controlled by the 120 Watt ATX power supply. The power supply plugs directly into the motherboard, adding nothing to the physical dimensions of the on-board system.

The median for all peripherals of the on-board system is a G5M100-N motherboard. This Pentium M ITX motherboard provides multiple I/O interfaces, RAM, and CPU on a single board. The ITX board has a distinct advantage over typical PC-104 boards that typically require distinct boards for processor, RAM, power, interfaces, etc. The ITX motherboard also accounts for a multitude of sensor suites and I/O devices to be added and removed from the on-board system with virtually no modification of the overall design due to low level integration of I/O ports. The ITX form motherboard also allows for an extremely thin designed enclosure where PC-104 boards are typically limited to a stack type configuration.

The on-board processing system is designed to receive GPS coordinates via the Superstar-2 5 Hz GPS receiver located within the enclosure and the externally mounted passive antenna.

Communications with the on-board system is handled via the 802.11 B/G Pro 2200 Mini-PCI wireless card that interfaces directly with the motherboard via the supported Mini-PCI slot. To support extended range, this card is wired to an external whip antenna mounted vertically to the front of the enclosure.

The remaining hardware consists of two serial to USB adapters which allow for communication with the GPS receiver and safety switch.

Several key requirements have been considered and identified before selecting the OS, including RS-232, USB, Mini-PCI device support, as well as installations requiring less than 500 Megabytes. These requirements have been based not only on current needs but also on the desire to adhere to future unforeseen modifications or add-ons.

One item neglected or overlooked intentionally so far is that the on-board processing system does not include any permanent storage. All software is stored on a USB stick plugged in externally when the system is booted. During boot, the entire OS is loaded into RAM from where it is accessed throughout the entire mission. After boot is completed, the USB stick is removed. Several issues have supported the decision to use a USB stick for boot: First, the software must be easily accessible and easily modifiable. A USB boot device permits booting from multiple variations of software including different operating systems and custom designed software. This type of boot also supports multiple platforms utilizing varying sensor suites by simply using a different USB stick. Second, on-board components needed to be minimal in both size and weight. Removing on-board storage reduces payload. Third, if the system is “use-n-lose”, this requires that the system software not be accessible to any one who might acquire the vehicle after it is “lost”. The vehicle’s lack of on-board storage, by definition, meets this requirement.

To adhere to the OS requirements the Slackware 10.2 installation of Linux has been chosen. This installation provides support for all currently required hardware as well as support for low level customization during installation. Specifically, it provides the ability to remove all unnecessary content (graphics, printing, etc.) from the OS allowing for a very small installation, less than 100 Megabytes, compressed. All previously mentioned OS customizations are done during installation and have added only about three minutes to the standard installation procedure. This system is also being tested with a 2.6.9 Real Time Linux kernel, to allow for future support of hard real-time software.

Four RC-truck ground vehicles and one helicopter have been built and tested.

## Autopilot

While the miniaturized on-board processing system presented in the previous section has proven extremely effective, future improvement to the designed system has been considered. Vehicle payload limitations, power consumption and requirements, cost-effectiveness and available ‘space’ on the unmanned vehicle must be looked at. In addition real-time control requires very strict and fixed timing for stability purposes. Because of this, it was determined that the embedded system approach in designing an autopilot could be utilized in order to compliment the on-board computing system in



addition to a stand alone processing system suitable for micro-air vehicles with very small payload capacities.

An initial design was developed that will provide a novel processing platform for unmanned systems. The design is fully integrated with MATLAB/Simulink allowing for both simplified high level programming and hardware-in-the-loop capabilities, and provides a flexible FPGA based platform that maximizes parallel processing and allows for analog signal conditioning that can be modified through digital communication from FPGA processor.

## Swarm Formation

The main objective of this work is to derive a simple method for robot swarm formation control as a whole. The desired control function characteristics are set as follows:

- Scalable, applicable to different size swarms
- Computationally efficient
- Supporting different (not fixed) formations
- Supporting centralized and decentralized formation control
- Homogeneous and heterogeneous swarms
- Expandable to aerial /ground vehicle swarms

A novel technique was developed for organizing swarms of robots into formation utilizing artificial potential fields generated from normal and sigmoid functions. These functions construct the surface swarm members travel on, controlling the overall swarm geometry and the individual member spacing. Limiting functions are defined to provide tighter swarm control by modifying and adjusting a set of control variables forcing the swarm to behave according to set constraints, formation and member spacing. The swarm function and limiting functions are combined to control swarm formation, orientation, and swarm movement as a whole. Parameters are chosen based on desired formation as well as user defined constraints. This approach compared to others, is simple, computationally efficient, scales well to different swarm sizes, to heterogeneous systems, and to both centralized and decentralized swarm models.

This technique was tested in both simulation and on hardware for a line and an ellipse formation with excellent results. The simulations were run in Simulink using both particles and a simplified RC-Truck model to represent the robots within the formation. The particles followed the vector fields exactly, allowing for a check of the mathematical implementation, while the robot models more accurately represented the swarm behavior through physical constraints such as limited steering. The swarm formation controller, which is identical for each robot/particle, is programmed in C. Each individual robot's vector generating controller is implemented as a C MEX S-function with the different control parameters fed in as well as a position vector with member locations. It is important to note, that knowledge of the other member locations are not a necessity except for the dispersion aspect of the swarm. The way the knowledge is shared could be done in numerous ways making a case for both centralized and decentralized robotic systems, but this is not the relevant point of the paper. The robots will hold to the bands of the ellipse regardless of knowledge of each other.

Results include:

- Four particles in a circle/square formation,
- Ten particles in a circle,
- Ten particles in an ellipse,
- Four robots circling a point,
- Four robots in a line,
- Ten robots circling a point,
- Ten robots in a line,
- Ten robots in an ellipse.

Experiments have used Traxxas Emaxx, RC-cars equipped with a custom built computer system. The Emaxx vehicles are Ackerman steered and each is equipped with an inertial measurement unit (IMU) and global positioning system (GPS). The UGVs are controlled via two servo commands, one command to control the speed, and the other the heading. Although each vehicle appears identical, each speed controller is slightly different and was tuned manually. The vector generation code is identical on every robot. The generated vector from is translated into two robot servo commands. A simple broadcast communication model programmed in C is used for information relay and exchange. Each robot shares its position with the other robots for obstacle avoidance purposes only since the robots currently have no other sensing capabilities to avoid collision. The robots were all programmed in C.

Experimental results utilizing four RC-Truck robots in an ellipse formation but with a simulated failure of one robot may be seen at <http://www.csee.usf.edu/USL/Videos/4-robotsfailure.wmv>

### Supervisory Controller for Mobile Robot Team

This research was initiated in order to develop a supervisory control to oversee a team of mobile robots that are able to work together as an automated system. This is significant in the area of robots utilized in industry where tasks are limited and predetermined but in a dynamic environment that may also be hazardous to human safety. Having a supervisory controller will ensure the interrupted operation of the team in case of robot failures.

A supervisory control model was developed to oversee a team of mobile robots in a warehouse patrolling application. This model was developed using finite state automata as a modeling tool. The supervisory control model is composed of a high level controller and a set of supervisory control modules. The high level controller activates the appropriate supervisor that redistributes the task assignments in the case of resource failures. The set of individual supervisory control modules observe the activities of the robots and only the active supervisor provides control feedback to the robot team. This design accommodates flexibility in tasks assignment, robot cooperation, task prioritization and sequencing to accomplish a set of objectives. The uniqueness in this controller design is that the events associated with the task assignments and completions, and failures and repairs are controlled separately by a hierarchical supervisory control model reducing real-time computational requirements.

## MANETs, Ad-Hoc Networks

The purpose of this communication research is to incorporate “Wireless Mobile Ad Hoc Network” (MANET) technology to examine the multi-hopping capabilities. To prove that a group of autonomous aerial and ground vehicles can extend the area of coverage, by relying information from distant sources to the main station through other “routing” vehicles.

A new capability was incorporated to allow the robots to be “connectivity knowledgeable” so they can modify their mobility pattern to make sure they are always connected to the MANET. This was done through using the physical layer such as the energy level of the nodes and the quality of the signals received. With this information was utilized to make a cross layer design-based control layer algorithm that finds and maintains stable links among the mobile nodes and the main controller.

A simple, accurate, and timely end-to-end bandwidth estimation technique for mobile ad hoc networks has been developed by addressing bandwidths random nature and its mean as a function of packet length. Also, this technique offers information such as range on which bandwidth takes values, or a confidence interval for the current mean. It is robust against cross traffic interference, and shows good adaptability, allowing users to choose a compromise of speed and precision.

*A Modification of the communication module in the swarming application* from all-to-all TCP sessions to UDP sockets where each robot sends the localization data through a unique socket that also receives information from every one.

In this modified version of mobile mesh 1 we corrected some initial bugs that did not allow successful compilation and we included a procedure that allows the user to know the internal routing table from mobile mesh, which is not accessible by default.

The *Execution Agent* application is running as a service in Linux. It receives requests from the user: a) hello messages that will be answered to show that the robot is active and listening, and b) commands that will be executed in the Linux system. This agent provided feedback about when a command request was received and when the execution ended. It works only with UDP packets.

The *Swarm GUI for the robots* is a Java-based application that interacts with the robots in three ways: a) send the requests to the Execution Agent in the robots, b) receives and presents the localization packets from the swarming application, so it can show the location of the robots in a relative coordinate system based on GPS coordinates, and c) receives the feedback from the control variables inside the swarming program.

The *TestConnections* application detects changes in the current trend of the radio signal status and determines when the robot must move to keep the connection alive between the robots.

The Sender Simple has the necessary code and procedures to include in the main application of the swarm to receive the feedback of the control variables to SwarmGUI. Receiver Simple is a light version of the application that will receive all the packets from the feedback and will show them in the standard output of the application.

Several experiments were carried out to demonstrate the multihop capabilities of the network in a cave scenario. Due to the lack of a real cave, we utilized the lab and the building as a cave and located one robot inside the building, another robot in the lab, and a third robot outside the lab. We sent data from the robot inside the building to the one

outside. The sender robot would not have had contact with the one outside the building, which shows the convenience of having the mesh network.

As expected, the communication between the first robot inside the cave and the control unit outside will drop soon after the robot starts going far into the cave. The purpose of this experiment is to find a way of detecting the detriment of the radio signal from the first robot, so more robots can be sent to create a bridge for multihop communication with the units inside the cave. Once the first robot enters into the halls of the building, the radio signal degrades as in a real cave but much worse. In our case, the shape and structure of the building makes the wireless environment very challenging, an environment where the receive signal strength (RSS) presents very high variability at all times. The identification and filtering methods implemented was based on window-based statistical method that calculates the average of the RSS and the 95% confidence intervals of the measurements in the moving window.

In order to experiment with the MMRP protocol, the first two protocols were installed in three laptops configured as the computers running on the robots. The main idea was to assess the performance of the ad hoc network in terms of throughput performance and multi-hop capabilities compared to the point-to-point solution currently in use.

Four scenarios were defined: Indoor, direct line of sight, no obstacles, direct communication; Indoor, no direct line of sight, no static obstacles (people walking), multi-hop communication; Outdoor, direct line of sight, obstacles, multi-hop communication (Configuration A), and, Outdoor, no direct line of sight, no obstacles, multi-hop communication (Configuration B).

The first experiment shows that the MMRP protocol is capable of transmitting video with excellent quality. The multi-hopping scenarios show that the throughput is approximately of 65 packets per second (9 frames per second) when using a 2-hop communication to send data with an acceptable quality in the channel. Even though this throughput is not of the best quality for video purposes, it is perfectly fine for the low data rate transmissions required by our application. Nonetheless, the experiments show that the multi-hopping feature works correctly, which is one of the most important objectives of the project.

## Navigation/Localization

### *Localization in Wireless Sensor Networks*

Localization is a key function in Wireless Sensor Networks (WSNs). Many applications and internal mechanisms require nodes to know their location. A new probabilistic distributed algorithm was developed for distributed cooperative localization, whose simplicity makes it amenable to self-localization in Wireless Sensor Networks (WSNs), characterized by their restricted resources in energy and computation. The algorithm is inspired in sequential Monte-Carlo estimation techniques, viz. particle filters, which excel in robustness and simplicity for estimation applications. However, particle filters require significant amounts of memory and computational power for managing large numbers of particles. This technique reduces the number of particles, while retaining the convergence, accuracy and simplicity properties, as demonstrated in simulation experiments.

With this technique, WSN nodes are assumed to host range-based measurement devices similar to those available in the Cricket location system. Assuming that each node hosts an ultrasonic transmitter and receiver, it can act as a beacon and a listener, although not at the same time. In the transmitting state, a node broadcasts chirps to neighboring nodes. Listeners compute their distance from the transmitting node and use the position transmitted by the beacon to update their own position estimates. Thus a “chirp” sent by a beacon is composed of an ultrasonic pulse and a short message (wireless packet) containing the location of the beacon and a measure of uncertainty in its own position. The main metric considered is the total amount of chirps broadcast to reach the final localization estimates. Therefore, the main concern is the convergence time of the algorithm measured by the number of chirps. Slower convergence times imply more messages being exchanged. The message complexity of the distributed algorithm employed for localization is essential to assess its impact on the energy consumption and the network lifetime.

MATLAB was utilized to simulate the localization algorithm using MATLAB scripts and functions consisting of only MATLAB primitives. The simulations consist of iterations of a basic step, where a beacon sends a chirp to its neighboring nodes. The nodes are deployed randomly within the field. Beacons that send chirps are picked at random. Nodes within the range of the beacon compute their distance from it and use this reading to update their particles. The computed distance has noise introduced that is assumed to be Gaussian. The simulations demonstrated promising results in establishing this new direction in location estimation techniques in Wireless Sensor Networks.

### Vision Based Depth Estimation and Collision Avoidance

A novel, simple and efficient method for vision based range measurements with uncalibrated cameras was developed. Required parameters are the image size, the relative distance between two different image frames of the same scene and the field of view of the camera(s). Range measurements acquired using ultrasonic sensors and a vision system have been used to navigate a mobile robot around known colored obstacles in an indoors environment. Both sonar sensors and cameras are activated and they operate simultaneously in parallel to obtain range measurements from common search areas located in the front of the mobile robot.

For implementation purposes, two types of obstacles have been used: Type I with size 50x60x30 cm and Type II with size 40x30x20 cm. Type II obstacles are colored yellow and cannot be detected from ultrasonic sensors because of their height, which is equal to the distance between the ground and the ultrasonic sensors. Type I obstacles cannot be detected from the vision system since they are not yellow. Multicolor obstacles are also used to illustrate capabilities of the approach in identifying different colors at different distances. Experiments have been conducted in an indoor lab environment with several “furniture obstacles” of different shapes, sizes and orientation, and with different lighting conditions. Experimental results confirm that the maximum computational error (as well as the normalized root mean square error) of range measurements using the vision system for obstacles lying at a distance of 27–800 cm

from the robot, is smaller compared to other similar, even more advanced and state-of-the-art existing approaches.

### Multiple Sensor UGV Localization

A method for localization of unmanned ground vehicles (UGVs) that are equipped with multiple sensors was developed and evaluated based on derivation of a fuzzy Extended Kalman Filter (EKF). The fuzzy EKF is used to fuse information acquired from the UGV odometer, stereo vision system and laser range finder in order to estimate the vehicle position and orientation. The noise distribution of the multiple sensor readings is identified via a set of Fuzzy Logic (FL) controllers also used to update the measurement covariance matrix of the EKF. Artificial landmarks are recognized by the stereo vision system and distances between the vehicle and the landmarks are computed by both the laser range finder and the stereo vision system. Each FL controller is dedicated to one sensor and its primary function is to adjust the parameters of the sensor readings noise distribution. Range information, odometer measurements and FL controller outputs are inputs to the EKF that estimates the current position of the vehicle. As a case study, experiments with a skid steering mobile robot navigating indoors and outdoors are performed, and obtained experimental results demonstrate that the fuzzy EKF performs better than the EKF in terms of position accuracy. More details and the results are given in “Multiple Sensor Based UGV Localization Using Fuzzy Extended Kalman Filtering”.

### Design of Controllers for Small Unmanned Helicopters

Small unmanned helicopter controller design is a rather challenging problem due to helicopter complex dynamics features, nonlinearities, gyroscopic effects, inherent instabilities and high degree of coupling among dynamic modes. Controller design is a major challenge that dictates model simplifications and linearization under certain constraints and around specific operating points.

However, small unmanned helicopter design and testing of simple, efficient low-level controllers that guarantee stable performance within a defined operational profile is achievable following small helicopter model simplification and linearization based on small Euler angle approximation and using diagonal dominance to determine conditions suitable to design decentralized controllers.

Initial work involved finding a systematic approach to deriving, testing and comparing simplified controllers using Computer Aided Control System Design (CACSD) tools such as MATLAB / Simulink, to achieve autonomous non-aggressive flights, putting emphasis on hovering/ slow flight patterns was derived. This method was first implemented with decentralized PID controllers, decentralized PID-like Fuzzy Logic controllers, and a centralized LQR controller. A comparison was made between the three types of control. Later work involved designing a Model Predictive Control system. While the previous methods yield good results in simulation, the MPC has the advantage of a higher level of robustness with less control effort.

The starting point is a 13th order state space model, Metler's model, derived for an R-50 helicopter. This model is based on the stabilities derivatives model, a parameterized linearized form of equations of motions where external forces and moments are represented through the derivatives product and the rigid-body vehicle's states and control inputs. It includes extending the stabilities derivatives model to account for coupled rotor-fuselage dynamics and the stabilizer bar dynamics to improve model fidelity. Partial derivatives of the forces (moments) with respect to the vehicle's states and with respect to inputs are termed stabilities derivatives and control derivatives, respectively, constituting the parameters of the model. Parameters' values are extracted from frequency response experiments through identification procedures.

Due to system dynamics' nonlinearities the state-space system parameters depend on the flight regime. The linear state-space system model describes helicopter dynamics with respect to the body-fixed reference frame for a specific flight regime. Transition from one regime to the next depends on helicopter actual inertial speed in the horizontal plane. Thus, parameters used for hovering/slow flight and cruising represent linearization of the body-fixed reference frame dynamics around two operating points. This model's main advantage is ability to obtain parameters for additional operating points, allowing for model extension under aggressive flights and for a more accurate description of associated nonlinearities.

Modal decomposition reveals insight information to helicopter instabilities, and diagonal dominance determines the level of coupling between model inputs, dictating under what conditions it is possible to follow a completely decentralized approach to design SISO controllers, sufficient to control the helicopter. Restricting the magnitude of Euler angles to less than  $2.5^\circ$ , diagonal dominances have relatively small values that allow neglecting couplings in the model.

The method followed is used for both inner- and outer- loop controller design. Two types of controllers have been derived following a similar procedure, optimized PD/PID and fuzzy PID-like controllers. Both controllers have been compared to each other and to an LQR MIMO controller for different flight profiles.

The major advantage of this method is the tutorial-like but simplified control design approach with proven justifications of how and when it is possible to follow a completely decentralized design approach to designing SISO controllers achieving desired performance objectives. Additional contributions include simplicity of such SISO controllers when compared to full MIMO designs, easiness of maintaining them, as well as ability of being enhanced in a straightforward way. The novelty lies in its simplicity and generality, as well as in providing insight information and justifications for controller design without affecting performance objectives.

A linear Model Predictive Controller (MPC) was designed and implemented in simulation for waypoint trajectory tracking of a small-scale unmanned helicopter. The controller developed shows a good robustness to parameter uncertainty. This MPC is based in a linear model considering input constraints. States constraints are also easily incorporated. The use of a linear model allows reducing the computational burden associated with the non-convex, nonlinear programming problem, which is generated when the quadratic components of the cost functions are substituted by the nonlinear model.

Main advantages for using/implementing MPC, also called Receding Horizon Predictive Control (RHPC), are:

- Ability to support constraints of variables associated with the control problem under study such as input, output or states variables;
- Its basic formulation may be extended to multivariable plants with almost no modification;
- Intrinsic compensation for dead time and no minimum phase dynamics;
- Ability to use future values of references when they are available, allowing MPC to improve performance in navigation such as waypoint trajectory tracking.

As with the previous control designs, utilizing Computer Aided Control System Design (CACSD) tools such as MATLAB / Simulink was taken into consideration. For that reason MATLAB's Model Predictive Control Toolbox, which has an interactive GUI, was utilized for interactive design of the controllers. This allows for repeatability of this work by others who may not be experts in the design of MPC.

The MPC controller was compared to the previously designed PID controllers for both an ascending spiral trajectory and a double circle with constant height. Both comparisons indicated a substantial improvement in the performance of the velocity tracking control and a marginal improvement in the position. The variations or changes in control signals of the MPCTT were minimal compared to changes needed in the PID velocity and position controllers. The same trajectory was tracked using the model parameters for the cruise mode. This change of operational mode requires substantial changes in the parameters. The MPCTT was able to track the trajectories with almost no changes. The range of the parameter changes were from 0% to more than 100% for some parameters. This indicates that the MPC is robust to those parameter changes.

## Fault Detection

The successful navigation and operation of complex dynamical systems, such as aircraft, spacecraft, UAV, UGV and unmanned undersea vehicles (UUV) is largely dependant on the reliability of sensors providing information for navigation and control. Redundant navigation sensors are often installed for measuring relative and absolute position of the vehicle in order to improve upon the safety and navigation. Among the information coming from the multisensor system, some can be erroneous or faulty. The reason must be either a sensor fault or a temporary inadequacy of the sensor in the operative environment of the dynamical system. The existence of a sensor fault can cause undesired reactions. As a result, on-line fault detection and isolation algorithms play an increasingly important part of the navigation system.

A model-based fault diagnosis system consists of a residual generation module and a residual evaluation module. Residuals are signals that, in the absence of faults deviate from zero only due to modeling uncertainties, with nominal value being zero, or close to zero under actual working conditions. If a fault occurs, residuals deviate from zero and the faulty conditions can be distinguished from the fault free ones.



A sensor fault detection and isolation system was derived and implemented on a UGV with both additive and abrupt sensor faults considered. Structural analysis was applied to the nonlinear model of the UGV and followed to build the residual generation module that is capable of detection single and multiple faults.

Two different residual evaluation solutions have been considered and experimented in real-time: a novel solution based on adaptive/moving threshold test, and a particle filtering-based likelihood ratio decision solution. Performance of both proposed residual evaluation modules were analyzed and compared. It was observed that the two proposed decision modules produced the same fault detection performances. However, the decision module based on the particle filter implementation requires more computational time, therefore, the novel adaptive/moving thresholds decision module may be preferable to use.

Experimental validation and exhaustive tests were done in real-time with both single and multiple faults. The testing was done on a differential drive ATRV-Jr mobile robot platform. The robot sensor suite includes a color camera mounted on a pan/tilt mechanism, Sick planar laser range finder, electronic compass, Garmin 16A GPS, odometers, wireless Ethernet connectivity and Crossbow's IMU 400CC-200, all connected to and integrated with the ATRV-Jr on-board computer (Pentium IV, 3.2GHz, 2GB Memory) through a Rocketport multi serial port card. Three sensors are used to evaluate the FDI system: Garmin 16A GPS, internal odometry and Crossbow's IMU 400CC-200. All experiments have been performed outdoors in an environment with several tall buildings (affecting GPS readings), vegetation and palm trees. The results obtained from the experimentation demonstrate that the FDI system is reliable and robust and easily applicable to different mobile robot platforms.

### Mobile Landing Platform

To increase the Miniature Vertical Take-Off and Landing (VTOL) vehicles range, a modified unmanned ground vehicle (UGV) can be used to transport the VTOL to its target area serving as an onsite take-off/landing and possibly refueling base. The gimbaled landing platform design is proposed to level the platform due to the pose (roll, pitch, yaw) of the UGV. To increase UGV endurance, a solar array is observed and solar tracking capabilities for performance maximization are examined. Simulations were carried out to check the validity of the design. The design is generic enough and suitable for many UGV/VTOL vehicles.

The chosen landing platform design is that of a gimbaled landing platform. The gimbal usually consists of 2 or 3 concentric rings that are connected with each other by axes, each of which is driven by an individual motor. As a result each ring can rotate independently of the other, keeping the inner gimbaled platform horizontal and free from vibrations. This is usually achieved with the installation of gyros, which calculate the angles of rotation of the platform, thus providing the necessary information to the motors to counter any movement of the gimbal support.

Based on research data it is possible to lower the ATRV-JR power consumption by about 50%. The reduction would not lower the quality or the number of sensors. By utilizing the landing platform as an alternative power source covered with a photovoltaic

array it is possible to keep the UGV powered when stationary without consuming battery power (weather permitting). The photovoltaic panels are very durable based on their usual uses within extreme weather conditions from snow and ice accumulation to its ability to withstand direct hail impacts. Therefore the array would be capable of supporting the weight of the VTOL and withstand the brute forces influenced during landing. Some considerations that must be posed are how the VTOL can be secured on the landing platform while the UGV is moving. A second consideration is if the VTOL is to be refueled by the UGV (either batteries, fuel or both). Recharging the batteries can be accomplished by taking advantage of using a securing mechanism and using the VTOL's skids as connectors.

In conclusion the research demonstrated the feasibility of a mobile landing platform for VTOL vehicles. The two-axes gimbaled design is proven to be adequate for ensuring a horizontal landing platform for a VTOL, even during the movement of the UGV. This platform allows a significant increase in the range of operation of miniature VTOLs and as a consequence an expansion in their areas of application. Additionally the design provides the opportunity for on-site energy production from renewable energy sources, thus further increasing the VTOL's as well as the UGV's endurance. Another advantage of the gimbaled platform is, that it can rotate around the z-axis that passes through its center and therefore can be used also as a mounting point for a camera, allowing a full 360° view. This latter feature allows tracking of moving objects even when the target object is behind the vehicle or traveling in parallel.

### Automated Process for Controller Design, Validation, and Hardware Implementation

A detailed step-by-step approach was developed in order to optimize, standardize, and automate the process of unmanned vehicle controller design, evaluation, validation and verification, followed by actual hardware controller implementation on the vehicle. The proposed approach follows the standard practice to utilize MATLAB/SIMULINK and related toolboxes as the design framework. Controller design in MATLAB/SIMULINK is followed by automatic conversion from MATLAB to code generation and optimization for particular types of processors using Real-Time Workshop, and C to Assembly language conversion to produce assembly code for a target microcontroller. X-Plane is used to verify, validate and optimize controllers before actual testing on an unmanned vehicle and actual implementation on a chip and printed circuit board.

This research has been motivated by the challenge to optimize, standardize, and automate as much as possible the process of unmanned vehicle controller design, evaluation, validation and verification, followed by actual hardware controller implementation on the vehicle. The presented approach is kept as general and generic as possible, so it is applicable to any unmanned vehicle with minor modifications that depend on the specific microcontroller processor and autopilot chip used. However, this paper focuses on and considers as a testbed miniature unmanned vertical take off and landing (VTOL) vehicles with very strict payload limitations and power supply restrictions using off the shelf components.

The rationale behind the attempt to 'automate' controller design, evaluation, validation and verification is manifold; it stems from the central objective to utilize the 'plug in – plug-out' concept of mission specific controllers. As such, given that unmanned vehicles in general, and unmanned helicopters in particular, are used in a multitude of applications requiring different controllers and mission profiles, rather than hard coding everything a-priori, it is deemed better to use application specific (low level) and (overall) mission controllers. This becomes more important given that, depending on a specific mission, flight patterns may change following non-aggressive or aggressive modes of operation that dictate different vehicle models (linear, linearized, nonlinear and approximations to linearization). For example, for non-aggressive flights, it is customary to follow a 'small angle approximation' that results in all sine and cosine functions being 0 and 1, respectively. Further, controllers are designed using mostly MATLAB/SIMULINK and then implemented separately in code. But when designing controllers in a programming language, changes are often tedious, so deriving a working controller requires not only considerable time, but it is also difficult to modify. In short, there is not a method that introduces a series of concrete steps to convert a controller (such as a PID, PD, Fuzzy Logic or an LQR) from MATLAB to implementation on a microcontroller chip.

The design process is as follows: Controllers are designed using MATLAB; Controllers using SIMULINK; Controllers are validated and verified using X-plane. This process is repeated and controllers are refined until desired results are obtained. Then: Controllers are converted to C code using the MATLAB Real-Time Workshop. The generated C code is for a target microcontroller or DSP chip. Additional validation and verification using X-plane follows, until the generated C code satisfies set requirements. C to Assembly conversion before the controller is implemented on the vehicle.

The validation/verification can be completed with alternative operational steps in which X-Plane may be used to check controllers twice, once (for controller validation after the initial design), or never assuming 'perfect initial controller design'.

Sample implementations were implemented. These involved the conversion of controllers designed for miniature unmanned helicopters (RAPTOR series) with very strict and limited payload, power, and processing capabilities is presented. The controllers designed followed the PID, Fuzzy Logic and LQR procedure presented previously in this report. Testing using X-Plane and a PID controller was done and demonstrated success. For portability between systems both C code and Java X-Plane communication implementations have been developed. In addition, interactions between landing a small VTOL on an ATRV Jr. have been tested through X-Plane and several of the plug-ins associated with the simulator. While the current version of the X-Plane/SIMULINK communication is applicable to non-predictive time based controllers, the SIMULINK solver has problems with maintaining real-time when the X-Plane SIMULINK block is run with controllers. However, this is not true if the block is run separately, so the problem lies with the SIMULINK solver and socket communication. This problem will be solved in a future version of the X-Plane/SIMULINK communication block through working with Mathworks and perhaps implementing the block as two separate blocks.

## Study on Improving Endurance of UGVs

UGV power requirements are mostly determined by the manufacturer for a specific vehicle configuration, ignoring the impact of possible upgrades, the addition of “off-the-shelf” sensors and other custom accessories. Given that a UGV has limited power availability, endurance and range are drastically affected by the on-board sensor suite and other peripherals. This dependence and restriction becomes even worse if and when the UGV needs to serve as the ‘base station’ and take off/landing platforms for small/miniature VTOL vehicles that require recharging upon landing on the UGV to continue their mission.

Research was conducted to consider restrictions and limitations on runtime and endurance as a function of a custom made vehicle and take off/landing platform, involving the ATRV-Jr. A comparative study was done of currently available battery and fuel cell technologies with respect to use with UGVs. From this research justified recommendations were derived that will improve upon endurance and runtime based on a priori set mission requirements.

This research determined that both the usage of only lead acid batteries and excessive power demand exponentially decreased the battery discharge time. Initial experimental analysis with comparative data suggested that for longer runtimes, it is first recommended to use lower power and more efficient sensors rather than over sizing the battery packs. Low power sensors, a Pentium mobile processor and a 90% efficient power supply may decrease consumption by 45%. The lithium ion technology not only meets the set energy requirements of 25Km/12hr goal with only 15Kg whereas lead acid technology would require more than 72Kg. Use of high energy cells such as VL45E and VL27M would provide the total mission energy demand with approximately one third less weight and volume. On the other hand, a combination of a DMFC (Direct Methanol Fuel Cell) and Li-Ion has an energy density of 105Wh/dm<sup>3</sup> and offers a runtime of 18 hours. The proposed DMFC and Li-Ion solution offers a refueling time of just a few minutes where Li-Ion alone requires several hours. Therefore, for outdoor applications such as search and rescue this combination is the most suitable for a design that must consider refueling time, weight, volume and runtime.

## Traffic Monitoring

This part is in addition to project objectives, evaluating unmanned helicopters in civilian domains.

Traffic simulation models are used to evaluate complex traffic behaviors and design alternative strategies to improve traffic control, minimize congestion and enlarge / modify traffic networks. They help predict future traffic demand, optimize signal timing and determine the need to improve roadway capacity. Traffic simulation models rely on collecting data from various sources and sensors, and then processing this data to generate study and evaluate traffic patterns and profiles. An integral part of this process includes model modifications and model parameter calibration based on updated data.

The advantage of using small unmanned helicopters to collect visual data is many-fold: helicopters hover over specific areas, can focus on data collection from a

specific link or intersection, can cruise repeatedly over a traffic link/component and they can fly in very low altitudes. They offer a very reliable way of collecting spatial-temporal data. This research capitalizes on small unmanned vertical take off and landing (VTOL) vehicles (helicopters) to collect real-time traffic data from network segments and use this data to generate (mathematical) statistical profiles to improve accuracy, parameter calibration and reliability of traffic simulation models, thus, improving traffic prediction.

For the purpose of traffic statistics, roadways are divided into interstates versus urban networks. In addition an urban network is further divided into links and intersections. The basic reason for differentiating links and intersections is that on links, vehicles interact only with other vehicles. That is, they need to change their behavior depending only on traffic flow or congestion. At intersections, vehicles also need to respond to signals and queue developments.

A method has been developed in which collected video data is incorporated into traffic simulation models improving real-time traffic monitoring and control. This is implemented by converting collected video data into 'useful traffic measures' that can be combined to obtain essential statistical profiles for traffic patterns. In essence, traffic parameters such as mean-speed, density, volume, turning ratio, origin-destination matrix, to name a few, may be derived accurately and be used to improve prediction of traffic behavior in real-time. Derived parameters being dynamically updated may serve as inputs to commercial traffic simulation models.

Data was collected using an unmanned helicopter with a fully autonomous pan-tilt vision system with one camera mounted on the helicopter hovering over the intersection of Alumni Dr. and Leroy Collins Drive, on the University of South Florida campus, in the morning hour from 7:00 AM to 8:00 AM. Counts/volumes were extracted and input into Synchro to update the traffic behavior. It can be observed that the traffic follows a certain trend depending on the direction of travel. Since the data is for only one hour (due to limitation of flying time), and cover only one intersection, major deviations in traffic are not noticeable. Though, it has to be pointed out, that this effort is to show that important information can be extracted out from readily available video data. In the future, the flying time and the observable area can be increased massively.